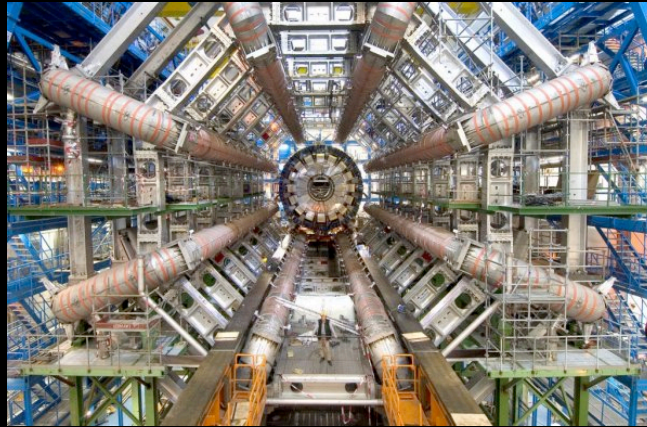


Exploring Nature's Fundamental Forces and Particles with the Large Hadron Collider

Beate Heinemann

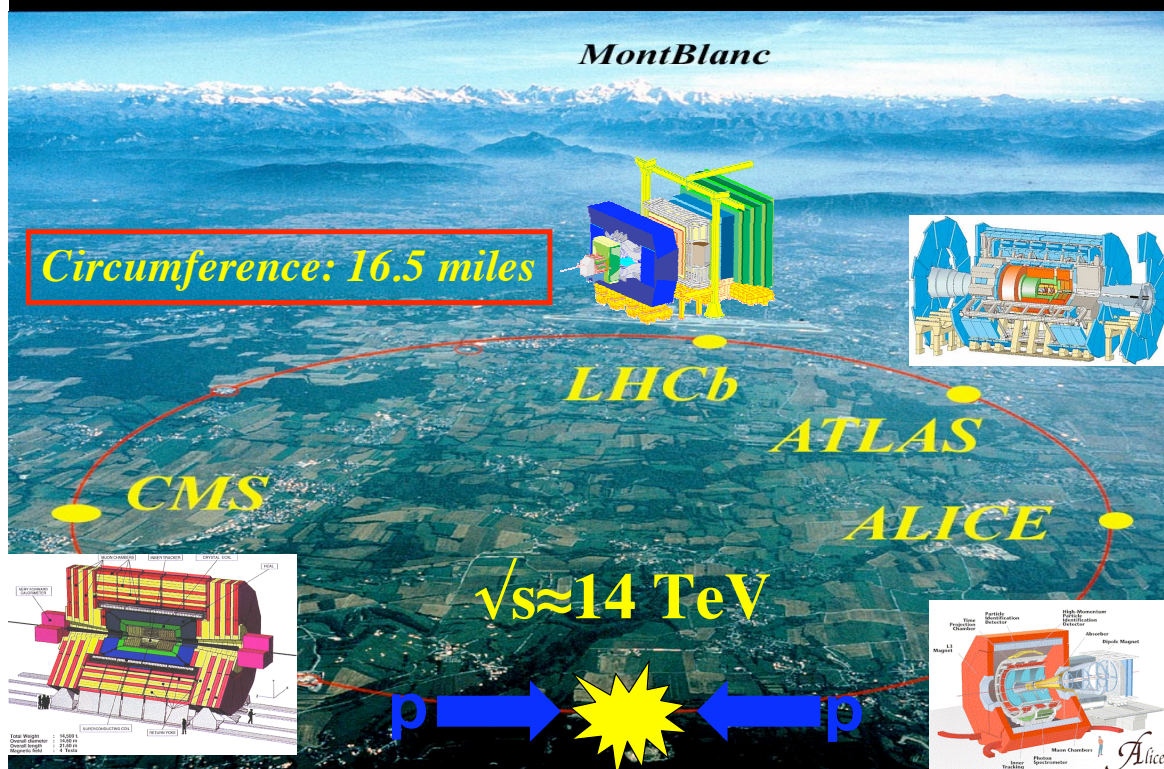
University of California, Berkeley and Lawrence Berkeley National Laboratory



Compass Lecture, UC Berkeley, April 2008

1

The Large Hadron Collider (LHC)



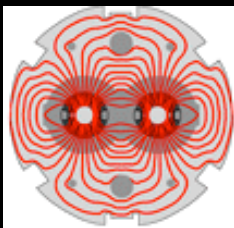
LHC in the Bay



- protons go really fast: 99.999999% of the speed of light
- make a full turn 11254 times per second

3

LHC Accelerator



- 30,000 tons of 8.4T dipole magnets
- Cooled to 1.9K with 90 tons of liquid helium
- Energy of beam = 362 MJ
 - Kinetic energy of 15 ton truck at 500 mph

4

Luminosity

- Single most important quantity
 - Drives our ability to detect new processes

$$L = \frac{f_{\text{rev}} n_{\text{bunch}} N_p^2}{A}$$

revolving frequency: $f_{\text{rev}} = 11254/\text{s}$
#bunches: $n_{\text{bunch}} = 2835$
#protons / bunch: $N_p = 10^{11}$
Area of beams: $A \sim 40 \mu\text{m}$

- Rate of physics processes per unit time directly related:

$$N_{\text{obs}} = \int L dt \cdot \epsilon \cdot \sigma$$

Efficiency:
optimized by
experimentalist

Cross section σ :
Given by Nature
(calc. by theorists)

Ability to observe something depends on N_{obs}

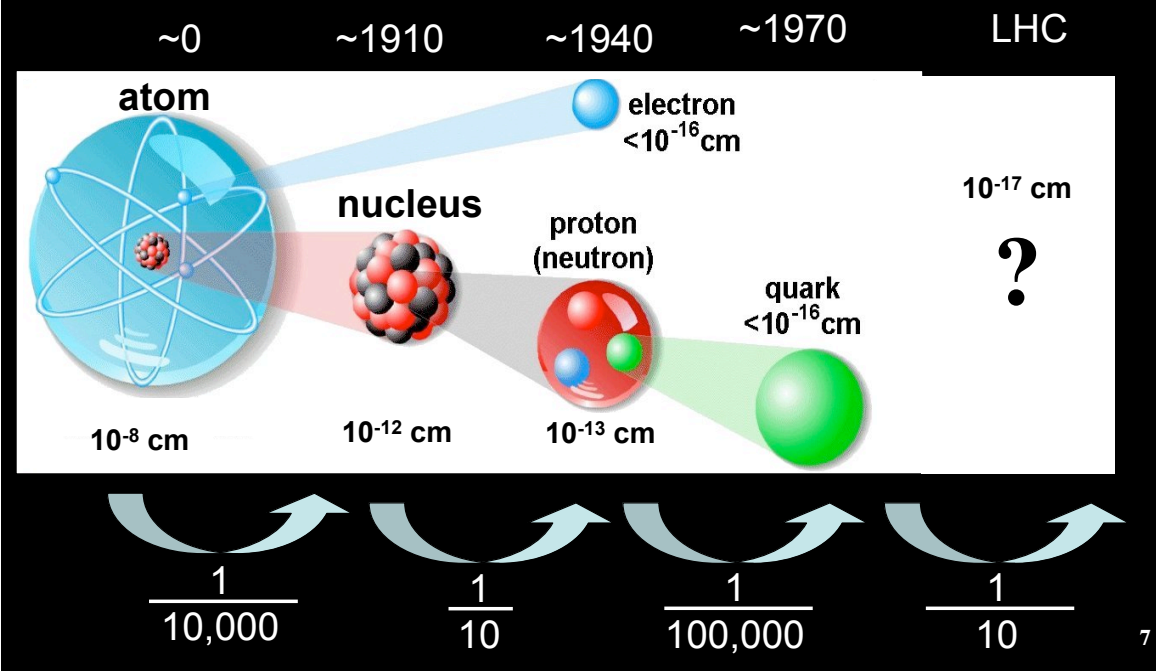
5

What Do We Hope to find at LHC?

- Answers to very fundamental and simple questions:
 - **Why do electrons have mass?**
 - Possible answer: The Higgs boson
 - **Why is gravity so weak?**
 - Possible answer: supersymmetric particles
 - **Or ultimately**
 - Does a Universe have to be like ours?
 - Or, is it random that ours is as it is?
- NB: This planet (and we!) would not exist if it was otherwise

6

We learned a lot in the last century



Elementary Particles: Matter

$\nu_e \nu_\mu \nu_\tau$ $e^- \mu^- \tau^-$ $u \ d \ s \ c \ b$
 $\bar{\nu}_e \bar{\nu}_\mu \bar{\nu}_\tau$ $e^+ \mu^+ \tau^+$ $\bar{u} \ \bar{d} \ \bar{s} \ \bar{c} \ \bar{b}$

top quark
anti-top quark

(Mass proportional to area shown but all sizes still $< 10^{-19}$ m)

Why are there so many **leptons** and **quarks**?
And, why do they all have **different masses**?

Origin of Mass

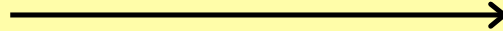
Nothing in the universe

Electron \longrightarrow
 $m=0.511 \text{ MeV}/c^2$

Photon \longrightarrow
 $m=0$

Top Quark \longrightarrow
 $M \sim 172000 \text{ MeV}/c^2$

Something in the universe



Higgs Particles interact with other particles the stronger the heavier they are:

- distance $\sim 10^{-17} \text{ cm}$ \Rightarrow will be found at LHC!

9

How the Higgs Field gives Mass

Cocktail party:
Guests are evenly spread



Arrival of celebrity:
Guests cluster near celebrity



D. Miller / UCL

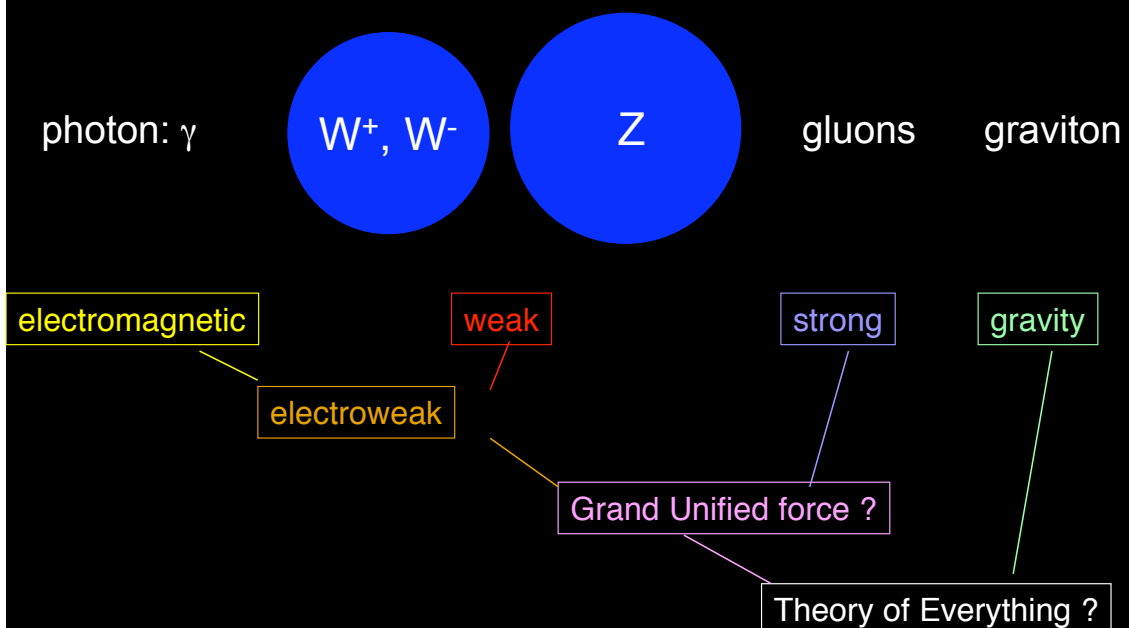
Celebrity loses momentum \Leftrightarrow acquires mass
(guests act like Higgs field)

10

Why is Gravity so weak compared to the other forces?

11

Elementary Particles: Force Carriers

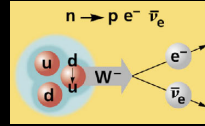


12

The “finetuning problem”

- Why is gravity is so much weaker than the weak force?

- Newton: $G_N = 6.67 \times 10^{-11} \text{ m}^3\text{kg/s}^2 \sim 10^{-38} \text{ GeV}^{-2}$
- Fermi: $G_F = 1.17 \times 10^{-5} \text{ GeV}^{-2}$



- Or why is the W boson mass so small?

- Weak scale: $M_W \sim 1/M_{\text{weak}} = 1/\sqrt{G_F} = 3 \times 10^2 \text{ GeV}$
- Natural scale: $M_{\text{Planck}} = 1/\sqrt{G_N} \sim 10^{19} \text{ GeV}$

⇒ “Finetuning” required to make W and Higgs mass small

13

Finetuning Problem

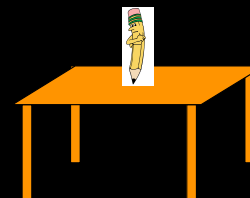
$$m_H^2 \approx (200 \text{ GeV})^2 = m_H^{\text{tree}} + \delta m_H^{\text{top}} + \delta m_H^{\text{gauge}} + \delta m_H^{\text{higgs}}$$

- Free parameter m_H^{tree} “finetuned” to cancel huge corrections so that

$$200 \text{ GeV} = 1763409820456210415 \text{ GeV} - 1763409820456210215 \text{ GeV}$$

- Isn't that Crazy!?!?

- Some unknown ad-hoc parameter introduced with superb precision
 - We were very lucky it worked out like this!
- Like finding a pen on a table like this

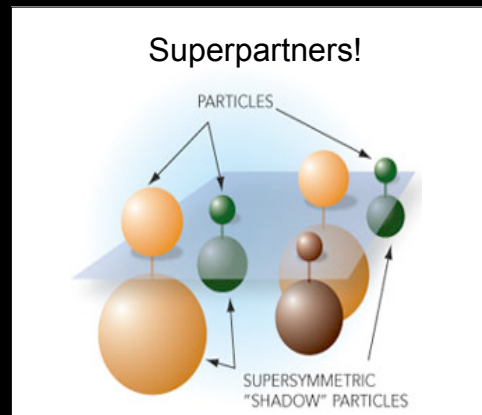
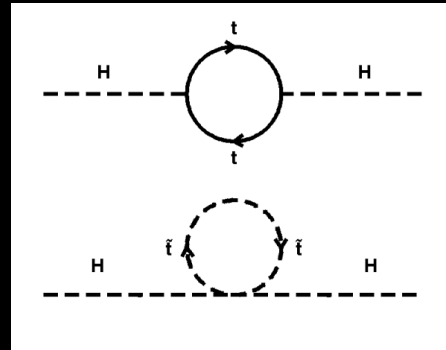


Seems wrong somehow

14

Solving the finetuning problem

- Add new particles
 - New loops cancel old loops!
 - Size of loops naturally the same
 - No hugely tuned ad-hoc parameter needed
- “Supersymmetric” particles
 - Each standard model particle has a partner, e.g.:
 - Electron => Selectron
 - Quark => Squark
 - Photon => Photino
 - W boson => Wino



15

Already happened in History!

- Might also seem crazy to have another set of particles introduced to solve aesthetic problem
- Analogy in electromagnetism:
 - Free electron has Coulomb field: $\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\epsilon_0} \frac{e^2}{r_e}$
 - Mass receives corrections due to Coulomb field:
 - $(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{Coulomb}}$
 - With $r_e < 10^{-17}$ cm: $0.000511 = (-3.141082 + 3.141593) \text{ GeV}$
 - Solution: the positron!

$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e} \ll m_e c^2$$

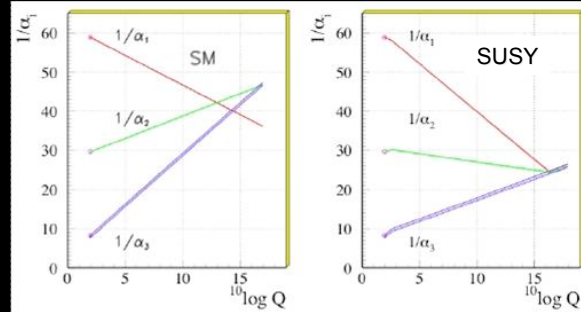
Hitoshi Murayama, UC Berkeley

Problem was not as bad as today's but it resulted in new particle species: anti-particles

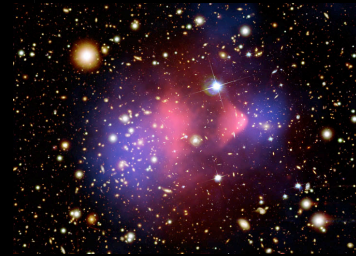
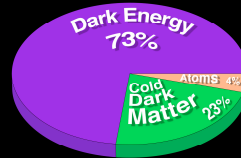
16

More virtues of Supersymmetry (SUSY)

- Electromagnetic, strong and weak force unify!
 - Miss unification in SM (barely)
 - Exactly unify in SUSY!



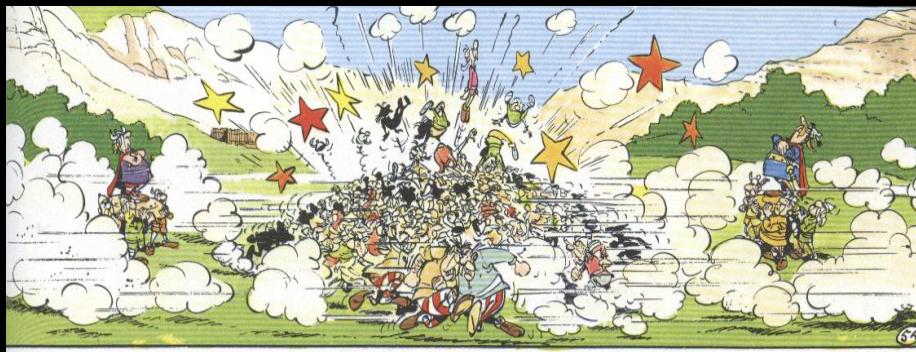
- Includes candidate for dark matter with 0.1-1 TeV mass
 - Cosmology data point to such a particle
 - 5 times more than ordinary matter



If SUSY particles are the solution to finetuning problem they will be found at the LHC

17

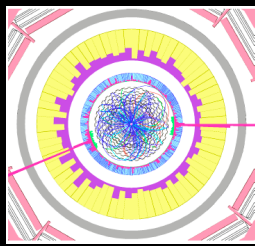
Proton-proton collisions



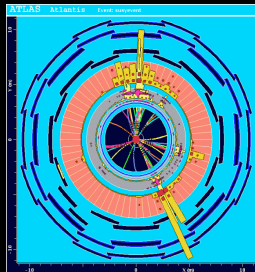
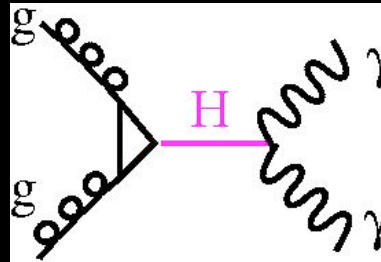
Complex events need to be resolved by clever detectors and physicists

18

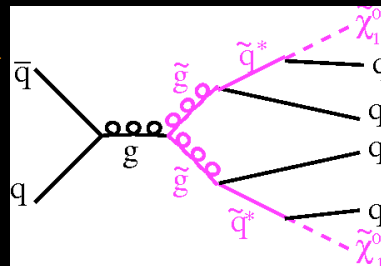
The Experimental Challenge



Higgs



Supersymmetry

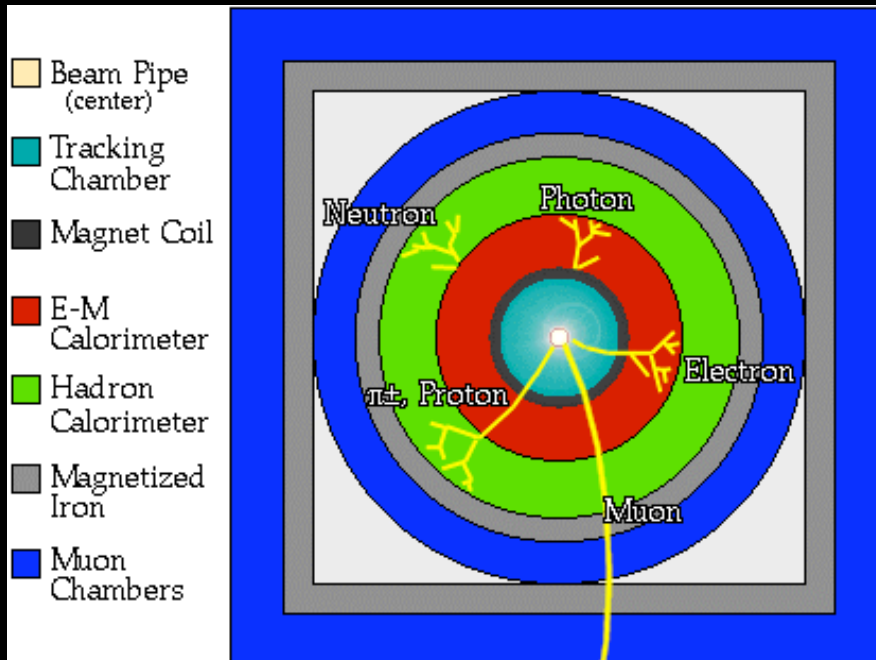


- Measured hits in detector
- => use hits to reconstruct particle paths and energies
- => estimate background processes
- => understand the underlying physics

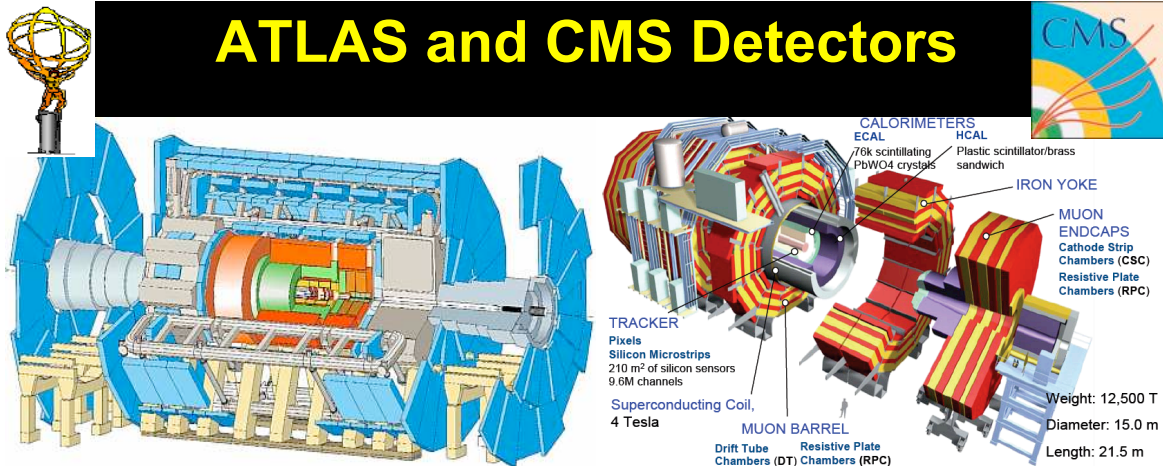
19

Particle Identification

- Detector designed to separate electrons, photons, muons, neutral and charged hadrons



20



	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

21

ATLAS and CMS in Berlin



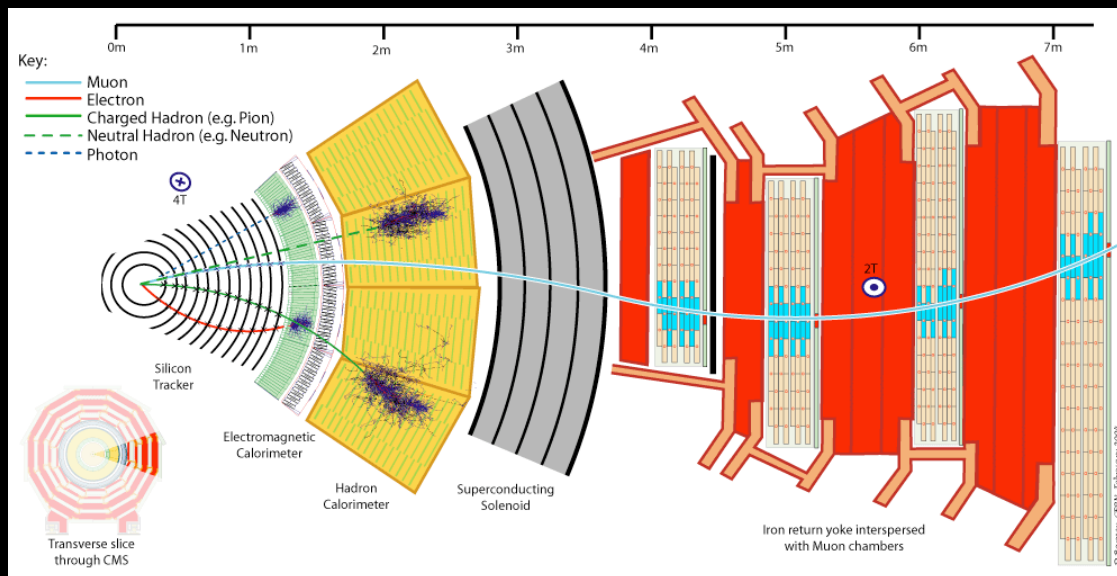
Detector Mass in Perspective



CMS is 30% heavier than the Eiffel tower

23

Detailed Layout

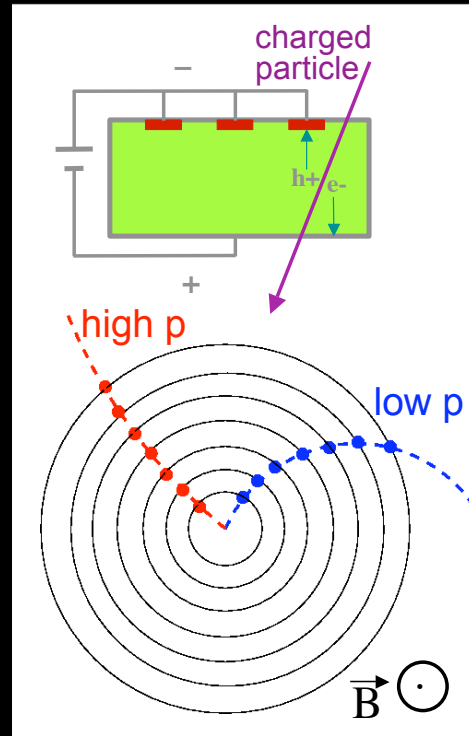


- About 100 million separate readout channels
 - 3000 km of cables

24

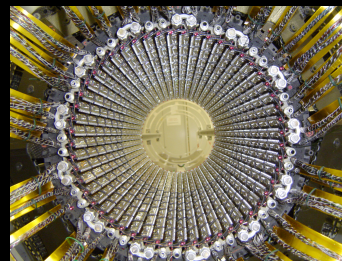
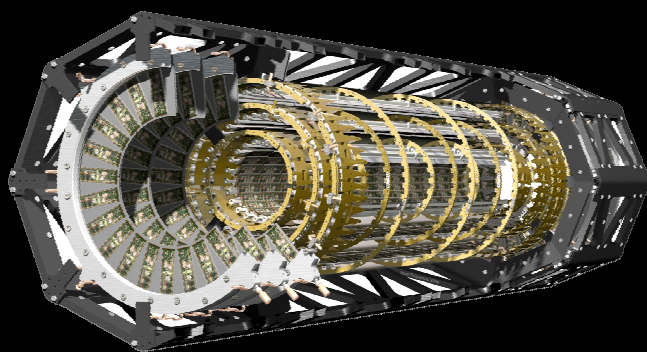
Silicon Tracking Detectors

- **Charged particle traverses silicon sensor (semi-conductor)**
 - Sets free charge carriers
 - Drift to electrodes
 - Measured charge gets collected at electrodes
 - Thus we find out position of particle
 - Resolution typically 15 μm
- **Detector placed inside magnetic field:**
 - Lorentz force: $F_L \sim q \mathbf{v} \times \mathbf{B}$
- **Hits along trajectory are fit to form a track**
 - deviation from straight line proportional to momentum ($p \sim v$)
 - Direction of curvature tells us the electric charge



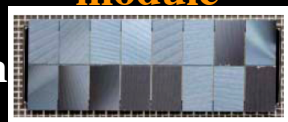
25

The ATLAS Pixel Detector

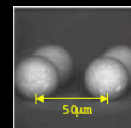


module

2 cm



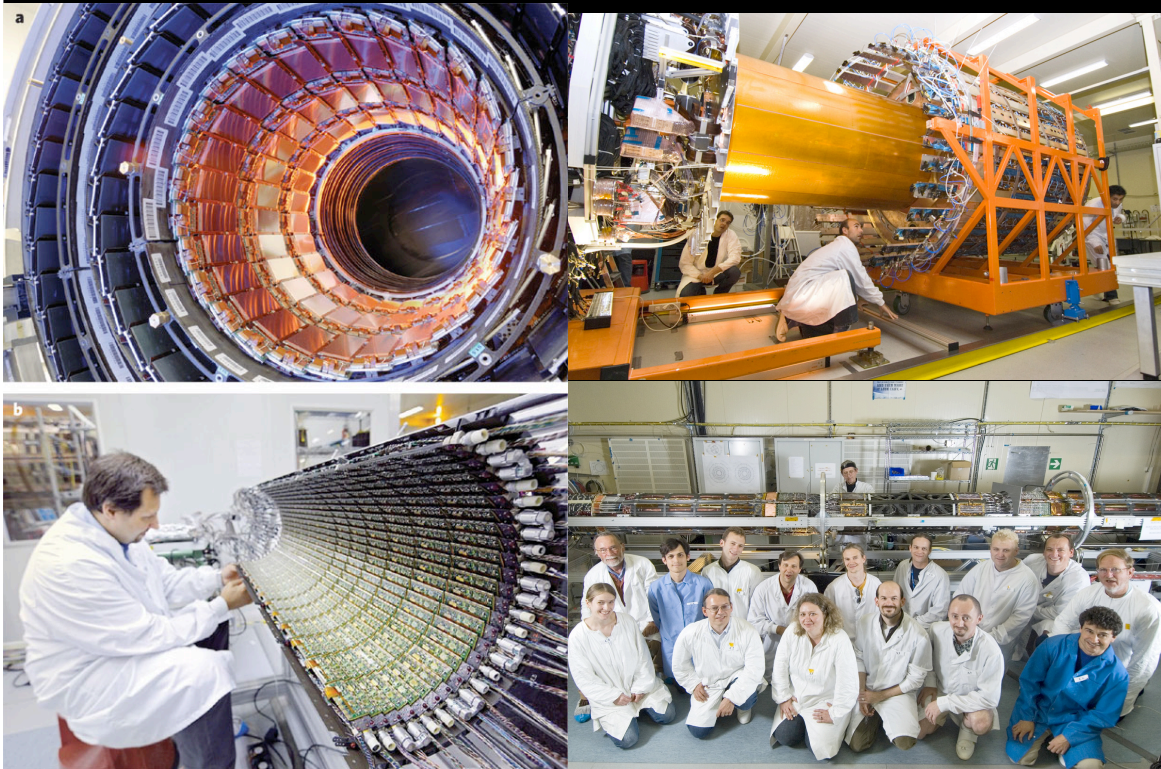
6 cm



- **Cylinder:** $L=1.4 \text{ m}$, $R=12.25 \text{ cm}$
- **80,000,000 individual pixels** arranged in modules:
 - 16 chips per module, 2880 pixels per chip \Rightarrow 46080 pixels/module
 - Distance between pixels: 50 μm ("pitch")
- **Designed and built largely in the United States**

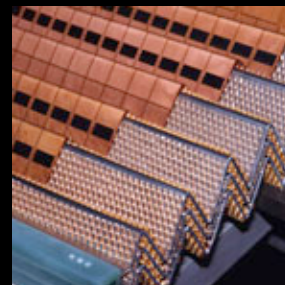
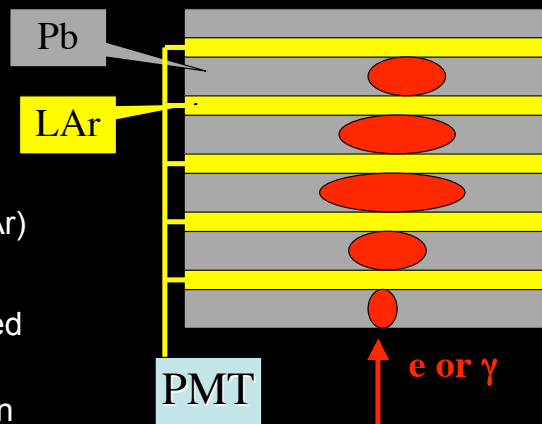
26

Tracking Detectors

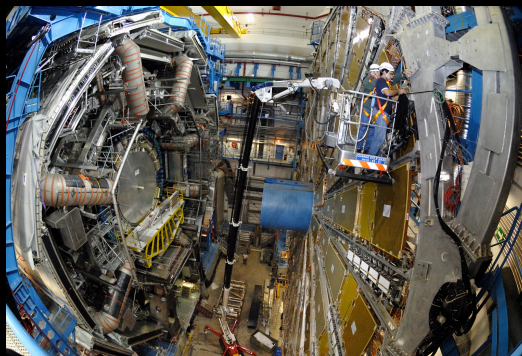
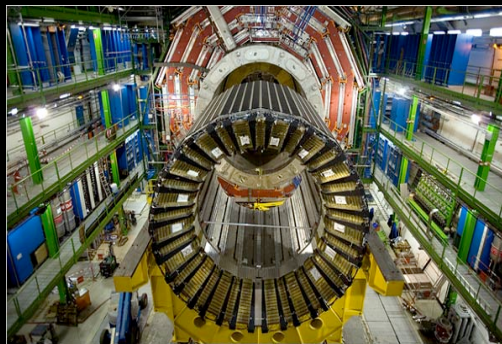
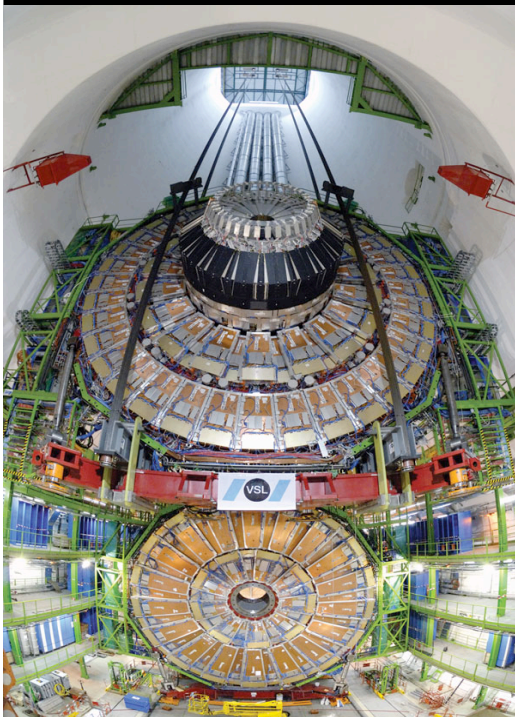


Electromagnetic Calorimeter

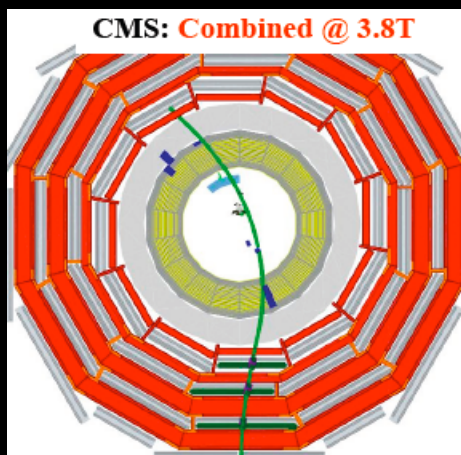
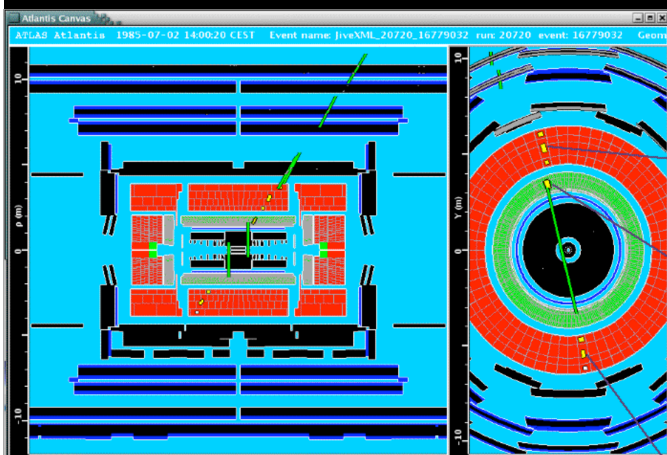
- **Sandwich structure:**
 - Absorber material: lead (Pb)
 - Active material: Liquid Argon (LAr)
- **Energy measurement:**
 - Electromagnetic shower produced through interactions with lead
 - Photons collected in Liquid Argon
 - $N(\text{photons}) \propto \text{energy of particle}$
 - Photomultiplier tube ("PMT")
 - Amplification of signal \Rightarrow readout
- **Position measurement:**
 - High spatial granularity \Rightarrow position known



Muon Systems and Calorimeters



Cosmic Muon Data



Experiments are currently preparing for LHC data taking - analysis of cosmic muon data



2000 Physicists from all over the World



(including 400 PhD students)
+ many technician and engineers

31

Enormous Data Volumes

- Pushing the computing limits!
 - 1 second of LHC data: 1000 GigaBytes
 - 10,000 sets of the Encyclopedia Britannica
 - 1 year of LHC data: 10,000,000 GB
 - 25 km tower of CD's (~2 x earth diameter)
 - 10 years of LHC data:
 - All the words spoken by humankind since its appearance on earth
- Solution: the "Grid"
 - Global distribution of CPU power
 - More than 100 CPU farms worldwide share computing power



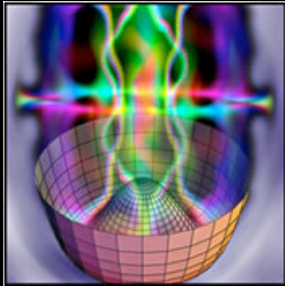
32

Some Example Analyses

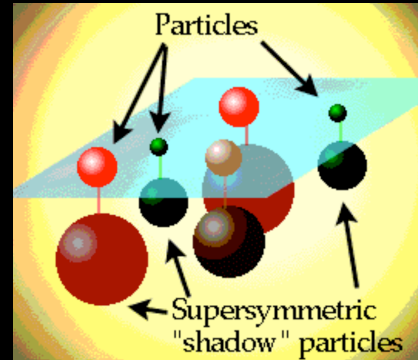
Finding the Higgs boson:

-with photons

-with Z-bosons



Finding a Supersymmetric World



33

Rates of Processes

- Everything happens probabilistically

Process	Rate
any	600 million / sec
$W \rightarrow e\nu$	10 / sec
Top quark	1 / sec
SUSY	<1 / min
$H \rightarrow \gamma\gamma$	8 / day

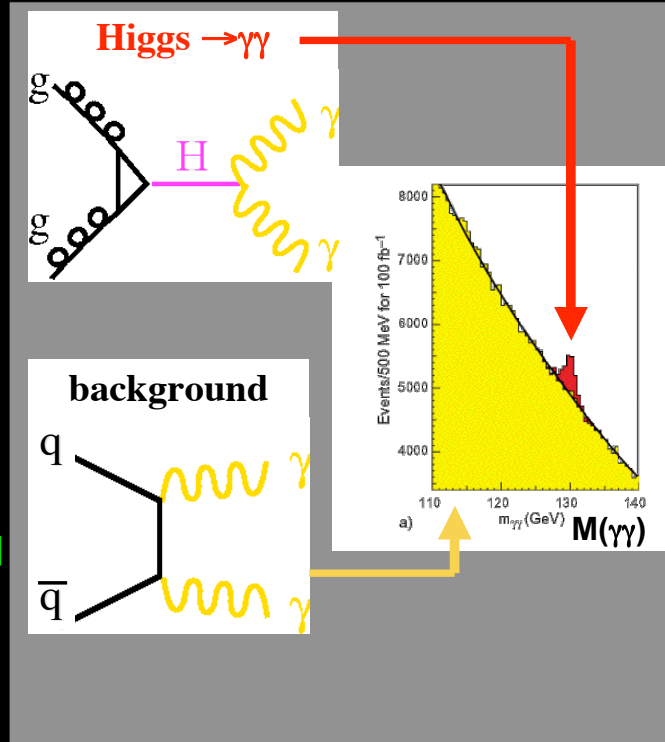
- And competing “background processes” that can be large
 - Key experimental work is to suppress/reduce and understand them

34

Finding the Higgs Boson (with photons)

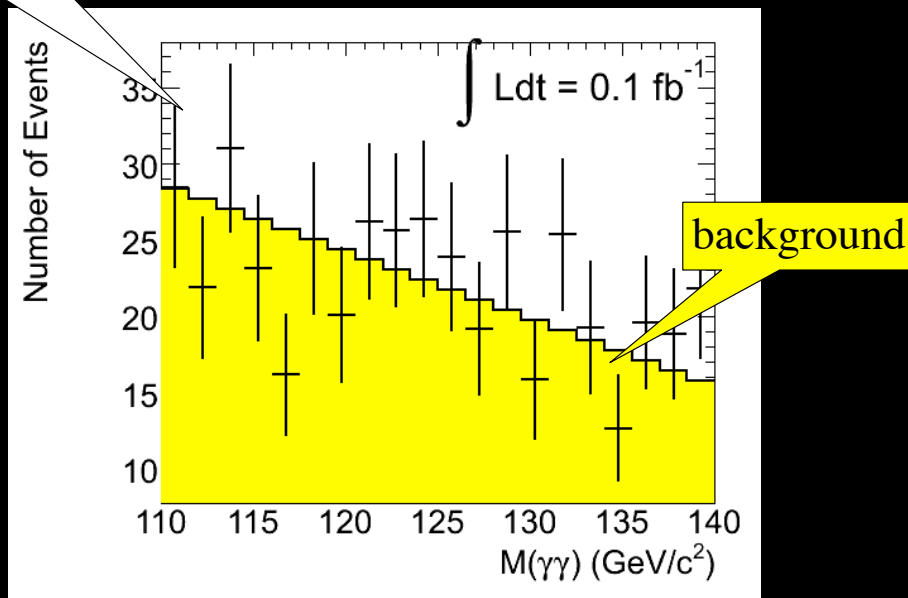
- Find 2 high energy photons
 - If $M(H) < 130 \text{ GeV}/c^2$
- Separate signal from backgrounds
 - Backgrounds can look exactly the same
 - but for γ 's from Higgs:

$$M(H) = M(\gamma\gamma) = \sqrt{[(E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2]}$$



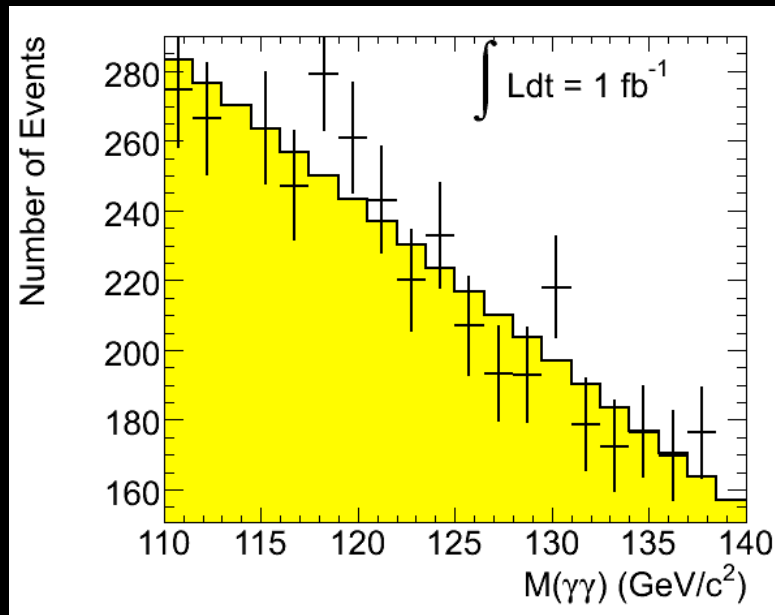
It will emerge with time

“Pseudo-Data”



$$\int Ldt = 0.1 \text{ fb}^{-1}: N_{\text{Higgs}} \approx 2 \text{ (year: 2008/2009)}$$

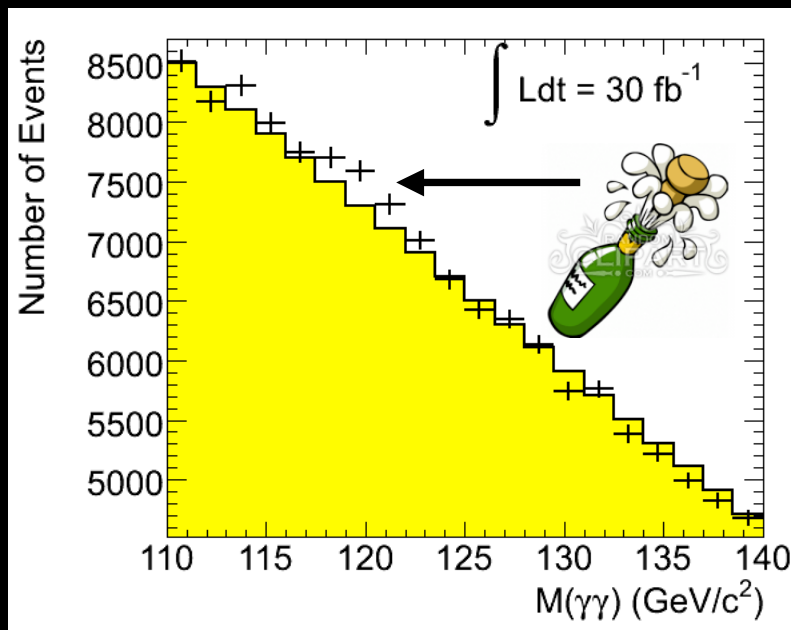
It will emerge with time



$\int Ldt = 1 \text{ fb}^{-1}$: $N_{\text{Higgs}} \approx 25$ (year: 2009)

37

There it is!

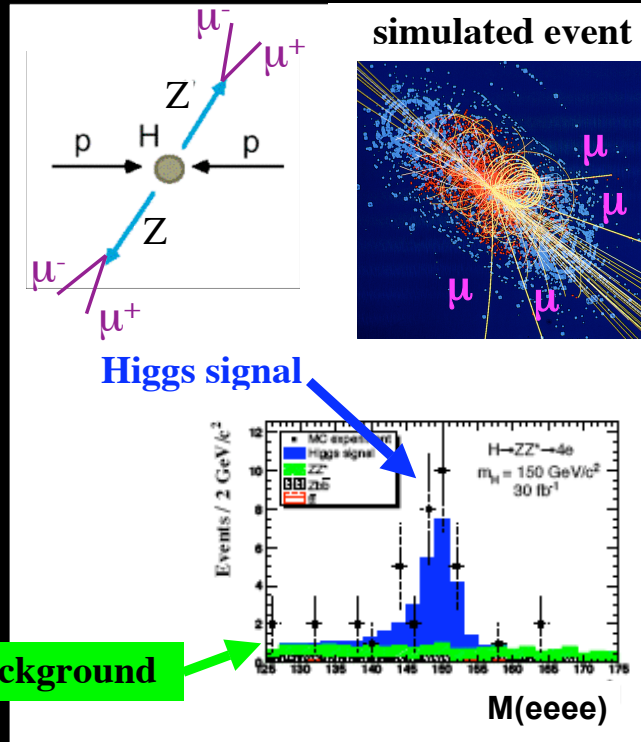


$\int Ldt = 30 \text{ fb}^{-1}$: $N_{\text{Higgs}} \approx 750$ (year: 2011/2012?)

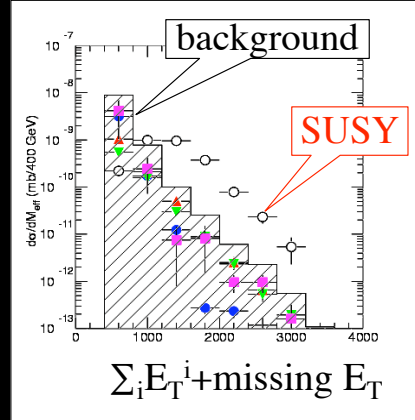
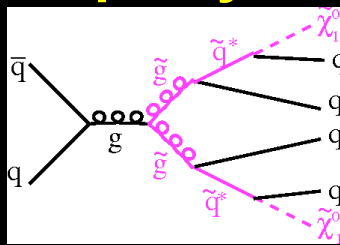
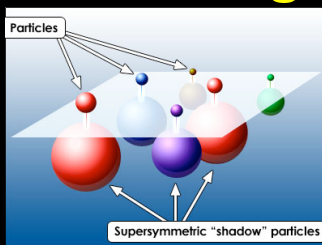
38

Finding the Higgs Boson (with Z's)

- Find 4 high energy muons or electrons
 - If $M(H) > 130 \text{ GeV}/c^2$
- Separate signal from backgrounds
 - Again calculating the invariant mass
 - Backgrounds much smaller than in diphoton case:
 - Easier!



Finding a Supersymmetric World



- Supersymmetric particles decay into ordinary particles:**
 - Measure decay products
 - Dark matter particle ($\tilde{\chi}_1^0$) escapes detector unseen:
 - Momentum balance tell us presence of dark matter particles ("missing E_T ")
- Search strategy:**
 - Search for many high energy particles plus large missing E_T

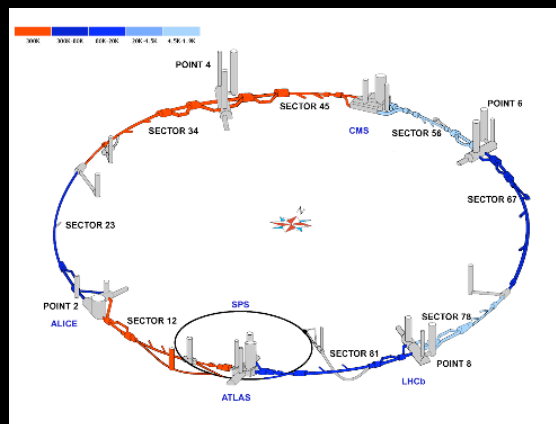
Might find the missing Dark Matter in the Universe

Many Other Possibilities...



H. Murayama, UC Berkeley⁴¹

When ? LHC Schedule



Conclusions

- **The LHC will finally probe the “TeV scale” ($r = 10^{-17}$ cm)**
 - Known to be special since 1934
- **After a 15 year design and construction phase the LHC experiments are taking data!**
 - Cosmic muons now, pp collisions later this year
- **Biggest experiments ever built**
 - >2000 physicists per experiment work towards a common goal
- **LHC will definitely answer some (and hopefully many) fundamental questions**
 - Within the next 2-5 years we'll know a lot more

43

Further Information

- CERN: <http://public.web.cern.ch>
- Particle Physics: <http://particleadventure.org>
- Experiments:
 - ATLAS: <http://www.atlas.ch>
 - CMS: <http://cmsinfo.cern.ch/outreach/>
(including many movies)

44